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The Space-based Telescopes for Actionable Refinement of Ephemeris (STARE) mission

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ABSTRACT

Recent events, such as the February 2009 Iridium 33-Cosmos 2251 collision, have brought attention to the changing nature of the Low Earth Orbit (LEO) environment. The population of objects recorded by the US Space Catalog has doubled since 1992, resulting in an increased risk of on-orbit collisions. USSTRATCOM's Space Surveillance Network (SSN) tracks resident space objects (RSO) and publicly releases a subset of these data to support conjunction (collision probability) analyses. However, these early warning systems did not prevent the Iridium – Cosmos collision. Conversely, there have been a number of high profile ISS false alarms where the crew has unnecessarily interrupted operations to take shelter. These examples highlight the need for better Space Situational Awareness (SSA) in LEO. The Space-based Telescopes for Actionable Refinement of Ephemeris (STARE) mission will improve SSA using a low-cost small satellite constellation. An operational STARE constellation of 18 nano-satellites will be able to assess greater than 99% of all conjunctions involving objects larger than 10 cm and has the capability to reduce the current collision false alarm rate by two orders of magnitude up to 24 hours ahead of closest approach, in effect reducing the number of actionable alerts to one per satellite lifetime. This is a significant improvement over today's capability, which provides so many false alarms (estimated at one per month per satellite for a LEO sun-synchronous orbit) that alerts are regularly ignored due to the inability of the space assets to move frequently.

INTRODUCTION

The space environment is increasingly being taxed as a result of successful commercial and government space programs. For example, communication satellites and global positioning satellites are now invaluable assets heavily relied upon by large communities. However, this success has come with issues such as orbital crowding, electronic interferences and an increase in space debris.

Mitigation of the space debris problem[1,2,3] through collision avoidance is currently based on information distributed by the United States Joint Space Operations Center and obtained through the Space Surveillance Network (SSN)[4], operated by the United States Air Force (USAF). The level of positional accuracy maintained by the SSN for the complete set of tracked space objects is insufficient to predict collisions with an adequate degree of certainty, and multiple false alarms occur daily as a result. Operators that rely on this system have to increase their margin of error to avoid potential collisions, a concept of operation (CONOP) that wastes fuel and shortens the asset's useful life. Because of the high false alarm rate—approximately one per month for the average, active satellite, or approximately 10,000 false alarms per expected collision—satellite operators typically choose not to maneuver their satellites based on these warnings, leaving the asset vulnerable to a true collision[5] as occurred in February 2009 between a derelict Russian military communication satellite and a US Iridium satellite, producing over 2,000 pieces of dangerous debris that could affect other satellites as well as the International Space Station.

Although the risk of collision was small for this particular encounter, the crash highlighted the need to have better tracking systems of items in space. Additionally, it raised the need to dispose of now defunct satellites. The SSN currently tracks over 20,000 manmade objects larger than ~10 cm in orbit around the Earth, and the NASA Debris Office estimates that as many as 300,000 objects larger than 1 cm are present in Low Earth Orbit (LEO) alone.

ORBITAL REFINEMENT NEEDS

An operational orbit refinement system should collect the information necessary to provide satellite operators with actionable collision warnings. What is needed is improved accuracy in the knowledge of orbital trajectories for those space objects that are predicted to pass close to an active satellite such that an operator can decide to use on-board resources, usually dedicated for station keeping, to move the asset. Space operators have to evaluate the trade-off between reducing the mission lifetime by utilizing non-replaceable resources and the mission failure due to a potential collision. Evidently, the level of certainty and frequency of notification on the potential collisions is a determining factor on the trade. The final aspect of the orbit refinement is the amount of time between the advance notice of the potential collision and the expected collision, since sufficient time is required to allow for the mission plan to be modified and executed. Based on those aspects, a set of high level requirements have been set for an effective orbit refinement system as shown in Table 1.

Table 1: Actionable orbital refinement system requirements

Requirement	Value	Flow down
Conjunction alarm rate per object	~ 1 during a satellite lifetime (~ 10year)	Satellite have limited moving capabilities (~1 time move)
Alarm advance notice	> 24 hours	24 hours needed operationally to orchestrate a move
Completeness	> 99%, objects > 10cm	Defined by stakeholders. To be adjusted

In order to assess the required refinement accuracy necessary to achieve the conjunction alarm rate specified, a full conjunction analysis was run on the entire Iridium constellation of 89 satellites (including 66 active, 6 spare and 17 failed but still in orbit satellites) against the full space object catalog for the period of April to May 2010 using historical available data and by varying the level of accuracy expected. Table 2 shows the number of warnings estimated to be received by the operator for the entire constellation.

Table 2: Iridium constellation (89 satellites) conjunction rate (April-May 2010)

Separation threshold	Notifications per Month	Notifications per Day	Relative Reduction
10,000m	36,574	1,219	
1,000m	354	11.8	99.03%
100m	3	0.1	99.99%

From this analysis, a 100 m threshold would reduce the number of notifications to a few per satellite lifetime enabling the space operators to take action with limited impact to their primary mission. It is to be noted that each notification would still have a low probability of being a true positive.

STARE CONSTELLATION PERFORMANCE PARAMETERS

This section first describes the STARE mission[9] through the overall CONOP supported by feasibility analyses, then details the constellation configuration trade-studies and finally computes the required metric observation accuracy.

Concept of operation

The STARE concept is based on a constellation of small, inexpensive spacecraft (nominally CubeSats).

The CONOPs for STARE are summarized as follows:

1) Generate a list of all potential collisions between 48 and 72 hours ahead using the publicly available low resolution catalog (uncertainty from 1 km to 10 km RMS)

2) Generate a schedule for all spacecraft in the STARE constellation, collecting multiple observations within the following 24 hours of all objects identified as being involved in a potential collision in step 1). In essence this step consists of identifying the close approaches of all objects involved in a potential collision with the STARE constellation and optimizing the available resources for maximum observation coverage.

3) Upload this observation schedule with pointing and timing information to the relevant STARE spacecraft. The upload makes use of the ground segment to ensure the shortest delivery time of the schedules.

4) Each spacecraft conducts the observations per the schedule and downloads the data back to the ground segment. The data collected contain time of observation, track end-point locations of the target[10], locations of stars in the field of view at time of observation, and global navigation system coordinates at the time of observation.

5) For each observation received on the ground, map the local pixel coordinates to celestial coordinates and apply correction factors (light travel time correction, aberration correction due to orbital motion, and sensor shutter timing characteristics)

6) At least 24 hours ahead of the expected collision, compute refinement orbits of both objects involved, using all observations received to date. Propagate the refined orbits to the expected time of collision. A new collision probability is generated based on the improved accuracy.

7) If the probability of collision is still high, notify space operator.

In the next few paragraphs, we will describe the different aspects of the trade-study supporting the concepts of operations that were performed for a STARE constellation. Parameters we considered include: orbital altitude and inclinations, Global Navigation Satellite System (GNSS) coverage, drag-limited orbital lifetimes and power budget.

Since the application is targeting orbit refinement and collision avoidance in LEO, it is natural that STARE spacecraft will also reside in LEO to maximize the number of observation available at reasonable distances. Figure 1 shows the number of observation opportunities per week covering a range of altitudes and inclinations. For this example, the target range has been limited to 100 km, and the transverse velocities (target relative to sensor) have been limited to 3 km/s.

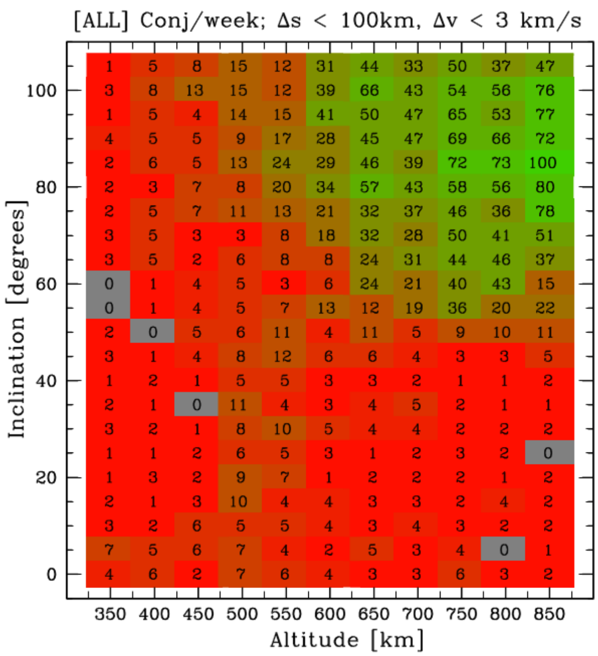

Figure 1: Weekly observation opportunities from various orbits to all objects in the NORAD catalog in April 2010. Observation range and transverse velocity limited for 100 km and 3 km/s respectively.

The number of potential collisions is directly linked to the density of orbiting objects. It comes as no surprise that the popular and crowded LEO sun-synchronous / polar regime accounts for the bulk of the conjunctions. STARE therefore, as a warning system, is best positioned just below this belt at about 700 km altitude, 100° inclination as indicated by the region in green in Figure 1.

Since the STARE observing platform is moving, there is a need to know where it is at all times. This is done using a GNSS fix from either the US based (GPS)[6], or the Russian based (GLONASS)[7] systems. However, it is not a given that STARE satellites can lock onto the required 4 or more GNSS satellites to obtain a fix from their optimal observation orbit. Figure 2 shows the time-fraction sufficient coverage can be expected, given a nominal observing schedule (satellite attitude affects locking efficiencies), and the antenna pattern. Only 20% of all the close approaches to potential collision objects would not have sufficient GNSS coverage at the time of closest approach. However, fixes obtained earlier and later in the same orbit can be used to infer the sensor location at the time of observation, thereby ensuring STARE sensor locations are known at all times to better than ~1 m.

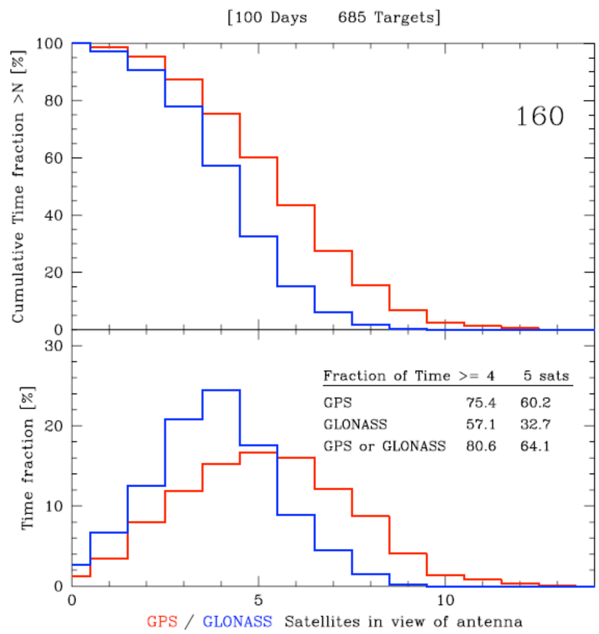

Figure 2: GNSS coverage analysis for a 700 km polar orbit conducted for a representative 100 day observation schedule with 685 targets. Antenna was assumed to have an effective angle of 172°.

Depending on the orbital altitude and the effective surface area of the satellite, the on-orbit lifetime is determined by the cumulative decay in semi-major axis due to atmospheric drag. Orbits that are below ~400 km do not last much longer than a few months, seriously impacting overall system performance. Much higher orbits, on the other hand, are non-compliant with NASA's 25 year limit[8], by remaining on-orbit for much longer than needed. For a nominal 3U CubeSat with 6 deployed solar panels, we determined a 7 to 23 year lifetime (depending on solar weather variations) at the optimum 700 km polar orbit. This is comfortably longer than the expected functional life-time, but also complies with existing regulations.

The satellite is powered through its solar panels, backed up by batteries. We need to assess how an observing schedule impacts the power reserves and whether dedicated charging periods are necessary. In general, each scheduled observation requires the spacecraft to orient away from the optimal charging attitude, potentially up to angles where no significant charging occurs.

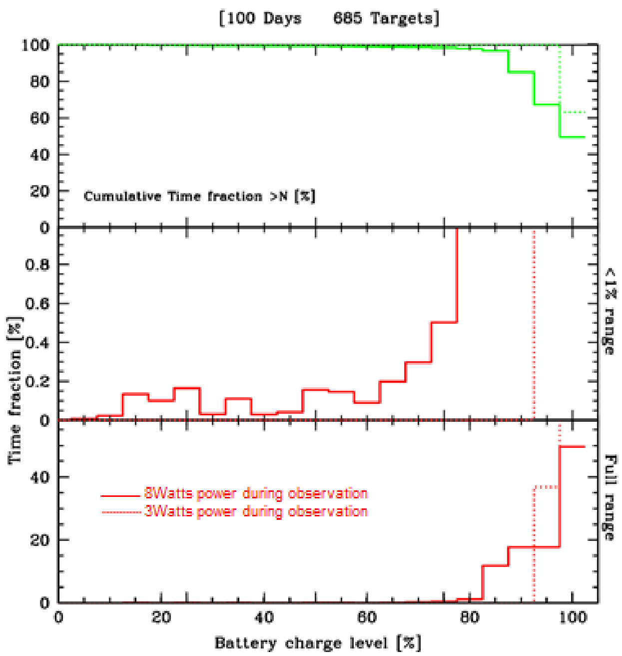

Figure 3: Power budget for a representative 100 day observation schedule for two power consumption rates during observation. Estimated collecting area of 0.15m^2 with 15% efficiency. Estimated storage capacity of 32W hour and with charge efficiency of 90%. Top – Cumulative time fraction the battery is charged to a level greater than specified, middle/bottom - cumulative time fraction the battery is charged to a level less than specified (two scales presented)

Further limiting charging are periods when the satellite enters the Earth's shadow. Figure 3 shows the power budget for a representative observing campaign, assuming a continuous 8 (or 3) Watt power consumption. The campaign is executed without regard for the current battery level, in other words, no attempts have been made to include charging cycles. Based on Figure 3, a typical 6 solar panel system with standard batteries can support the CONOP while ensuring that the spacecraft is power positive at the 3 W level. At larger power footprints, on occasions the observing mode will have to defer to a charging mode.

Constellation design

Table 3 lists various constellation configurations we considered to meet the basic STARE CONOP. All are based on the optimal 700 km altitude polar orbit, with the main variation between the configurations being the number of spacecraft and the number of orbital planes. Furthermore, additional constraints like maximum observational range, observational time window, and number of observation per objects are considered (Figure 4).

The optimal configuration for an operational constellation, where we limit the number of satellites to 18 to 24 and the maximum observation distance to 1000 km, while retaining better than 95% completeness within 24 hours, is between the '3P6' and the '3P8' configuration. In other words, 3 polar planes, staggered by 60°, each occupied by 6 to 8 satellites.

It should be noted, however, that the exact orbital configuration is less important that having good coverage of the 4π steradian sky, and as such, strict adherence to orbital regimes requiring station-keeping is not necessary.

Table 3: STARE constellation trade configuration evaluated

Code	Constellation configuration
One	Single satellite in a 700 km circular polar orbit
1p2	2 satellites in a single plane (700 km, circular, polar orbits)
3p1	3 satellites each in a plane (700 km, circular, polar orbits)
1p4	4 satellites in a single plane (700 km, circular, polar orbits)
3p2	6 satellites, 2 in 3 planes (700 km, circular, polar orbits)
6p1	6 satellites each in a plane (700 km, circular, polar orbits)
1p6	6 satellites in a single plane (700 km, circular, polar orbits)
3p4	12 satellites, 4 in 3 planes (700 km, circular, polar orbits)
6p2	12 satellites, 2 in 6 planes (700 km, circular, polar orbits)
6p4eq	24 satellites, 4 in 6 planes (700 km, circular, polar orbits for 3 plane, one plane equatorial)
3p6	18 satellites, 6 in 3 planes (700 km, circular, polar orbits)
3p8	24 satellites, 8 in 3 planes (700 km, circular, polar orbits)
6p4	24 satellites, 4 in 6 planes (700 km, circular, polar orbits)

Track fitting accuracy

One of the driving requirements needed to implement STARE is to obtain an orbital refinement with accuracy better than 100 m (rms). The level of orbital refinement is linked to the level one can measure the target position via the track end-points with respect to the celestial coordinate frame (see step 5 of the concept of operation flow). We used historical TLE data on SaudiSat2 in a modeled campaign of up to 4 observations at a range of 200 km from a single emulated STARE satellite. As shown in Table 4, a fitting accuracy of 10 arcsecond (~50 micro-radians) on the track end-points is sufficient to achieve better than 100 m (rms) orbital refinement accuracy after just three observations.

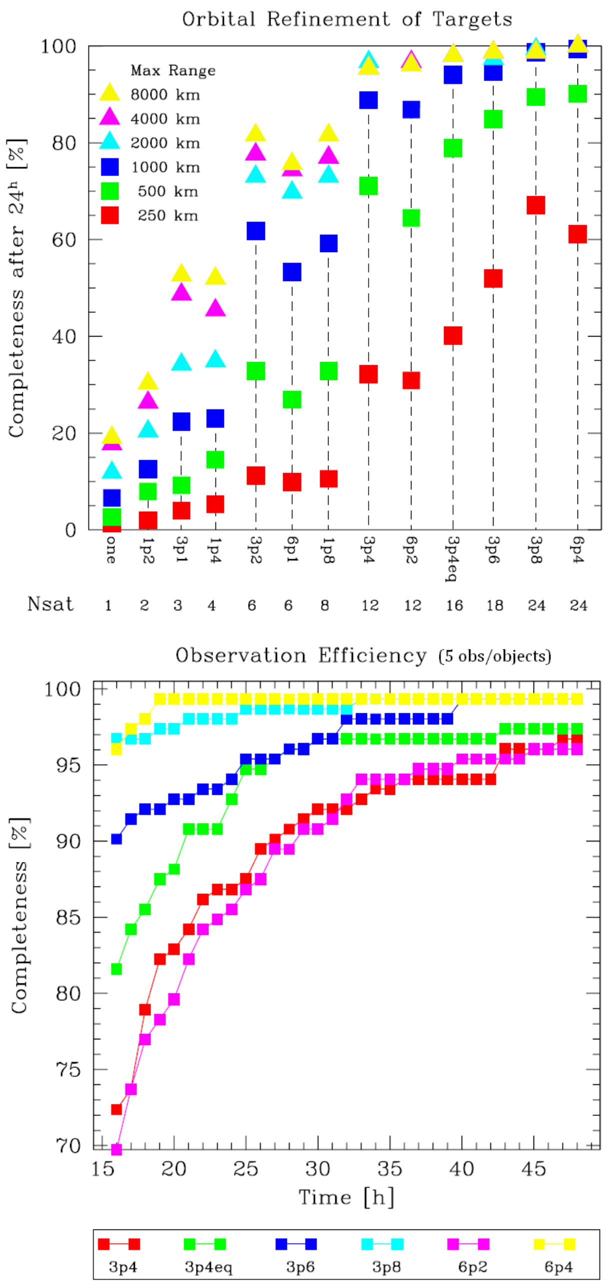

Figure 4: STARE constellation observation time trade study. a) observational range dependent performance of various constellations with 48 hour notice, b) observation time performance with 5 observation per objects.

As the observation range increases from 200 km to 1000 km, additional observations are needed to retain adequate orbital refinement accuracy. In general, an operational STARE constellation will collect between 5 and 10 observations to account for this effect.

Table 4: Set of 4 observations for SaudiSat2 for a modeled campaign with various track end-point fitting accuracy (RMS) and expected orbit refinement uncertainty (RMS) after use of the combined data

Fitting Accuracy (arcsec)	Initial Uncert. (km)	1st Obs Uncert. (km)	2nd Obs Uncert. (km)	3rd Obs Uncert. (km)	4th Obs Uncert. (km)
1.8	1.101	0.339	0.099	0.040	0.019
3.6	1.101	0.347	0.111	0.069	0.036
7.2	1.101	0.361	0.124	0.096	0.063
14.4	1.101	0.378	0.154	0.111	0.093
28.8	1.101	0.388	0.214	0.116	0.110
115.2	1.101	0.401	0.309	0.125	0.123

Mission specification summary

Based on the CONOP described in the previous section and the supporting analysis and trade-studies, a set of performance requirements have been selected for implementing the STARE mission as shown in Table 5.

Table 5: STARE Mission Requirements flowed down from Table 1

Requirement	Value
Uncertainty refinement	< 100 m from < 10,000 m < 10″ fitting accuracy > 5 observations/object
Constellation size	> 12, <18
Range	> 200 km, < 1000 km > 10 cm
Relative velocity	< 10 km/s
Observation time	48 hrs (72hours before conjunction to 24 hrs before conjunction)
Orbital configuration	3 polar planes, 700 km

STARE SPACECRAFT FUNCTIONAL REQUIREMENTS

Based on the STARE mission overall requirements, a set of key requirements can be flowed down to each spacecraft. Those performance requirements mainly pertain to the fitting accuracy and the signal to noise required and can be summarized as follows:

1) Fitting accuracy to better than 10 arcsecond (flowed from orbit refinement to less than 100 meters uncertainty)
2) Field of view greater than 3° by 3° (flowed from initial uncertainty knowledge up to 10,000 m, differential velocities less than 10 km/s and minimum range of 200 km with integration time set at 1 sec)

3) Sensitivity to better than 10 cm sized objects at ranges greater than 1000 km, 10 km/s relative velocity (flowed from constellation size of greater than 12 satellites with better than 99% completeness 24 hours in advance of conjunction)

Table 6: Track-end point fitting accuracy allocation based on available technology performance.

Contribution	Allocation (arcsec. RMS)
Telescope (5″ per pixel)	7″
Astrometry error using ~20 stars (~0.75 pixel)	3.75″
End-Point fitting accuracy with SNR > 4(0.7 pixel)	3.5″
Star centroid error due to pixel active area shape (< 0.5 pixel)	2.5″
Star centroid error due to optical aberrations (< 0.5pixel)	2.5″
GPS positional uncertainty (< 7 m)	7″
Special relativistic correction due to motion of orbiting platform (Correction of up to 20″, with small residual errors less than 1″.)	1″
Light speed correction from orbiting platform to target (Correction of up to a few milliseconds with small residual errors less than 1ms)	1″
Timing accuracy of exposure (< 1 millisecond)	1″
TOTAL	**10″**

Contributions to the fitting accuracy are broken down in Table 6, and include components due to the accuracy in determining the stellar locations and track-end points at the pixel level, as well as terms related to the celestial mapping and actual time of observation.

Table 7: Nominal point spread function allocation based on available technology and signal to noise requirements

Contribution	Allocation (PSF FWHM)
Telescope + sensor	1 pixel (5″ FWHM)
Attitude Control stability	1.4 pixel (3″ RMS)
TOTAL	**1.8 pixel**

One of the main drivers determining sub-pixel track end-point fitting accuracy is the signal to noise of the track[10]. This essentially drives the noise performances of the sensor as well as the optical telescope aperture and the overall point spread function (PSF) of the system. The PSF of the system is the combination of the optical performances and attitude control stability during the exposure time and is shown in Table 7 for available technologies.

Note that given the 10 arcsecond fitting requirements, the optical systems do not have to be diffraction-limited for the relevant apertures (7 cm to 9 cm for the 3U CubeSat form-factor).

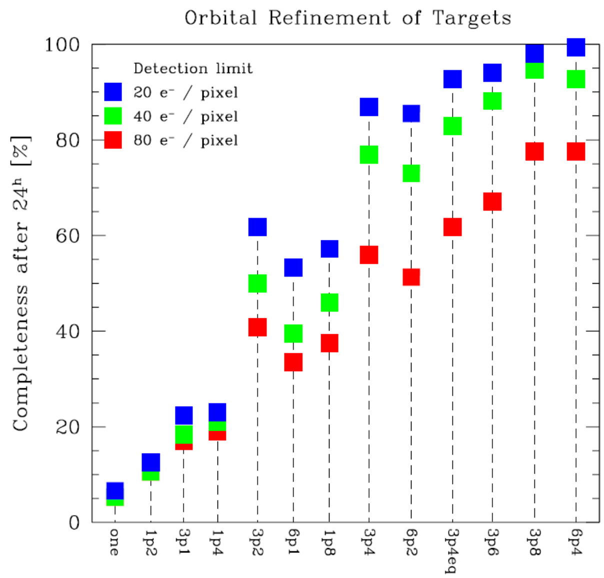

Figure 5: STARE constellation performances for different detection limits (Quantum efficiency set at 60%). The scenario used here assumed 152 possible conjunctions to refine in one day with 5 observations per targets.

Figure 5 demonstrates the graceful degradation of the overall constellation performance as the signal requirements for detection increase. Requiring brighter streaks reduces the number of possible observation opportunities per day, however, most of this can be recovered by collecting over a longer period as more favorable observing opportunities make themselves available (i.e., collect over 36 or even 48 hours instead of 24).

STARE PRELIMINARY RESULTS

Lawrence Livermore National Laboratory (LLNL) has conducted a spiral development of the STARE technology through 3 pathfinders. Each pathfinder is a 3U CubeSat and each builds upon technology maturation developed on the previous pathfinder. The first pathfinder was launched on the NRO-L36 OUTSat[11] mission on September 13th 2012 and has experienced communication issues being investigated at the time of writing. This first pathfinder has a Cassegrain telescope and an attitude control capability limited to torque coils. The second pathfinder, implementing a full set of reaction wheels for attitude control and a more sensitive imager, is manifested to launch on the ORS-3 mission and expected to launch in the fall of 2013. The third pathfinder, implementing improved reaction wheels and a compact and robust optical telescope, is expected to launch on the NRO-L39 GEMSat mission[11], also in the fall of 2013.

Table 8: NORAD 27006 orbit refinement performances using the STARE pathfinder flight hardware. Refinement was conducted using the first 4 observations and compared against the last two observation used as true reference

Obs. number	Delay [hours]	Obs. range [km]	End point	Error in STARE Prediction vs. Measured [m]	Error in TLE Prediction vs. Measured [m]
5th	12.75	1526.737-1529.293	START	24.9	520.75
			END	54.6	614.64
6th	35.5	1277.265-1279.703	START	30.0	575.74
			END	29.3	526.34

Ground validation of the performances of the flight hardware has been conducted during a set of ground campaigns. In particular, the second pathfinder flight hardware has been used to collect a set of 6 observations between January 14th 2013 and January 16th from the LLNL site on a spent rocket body. The target is an SL-16 Rocket Booster (R/B, NORAD ID 27006) of the Soviet Zenit family with a perigee of 992 km and an apogee of 1014 km.

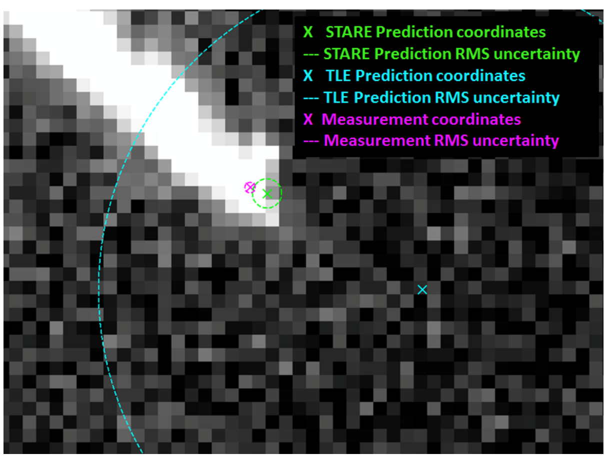

Figure 6: NORAD 27006 orbit refinement performance after 4 observations using the STARE pathfinder flight hardware overlaid on the 5th observation image 12.75 hours after the 4th observation.

It has a length of 32.9 m and a diameter of 3.9 m, providing an average visible magnitude of ~3.8. It has an inclination of 99.1°, enabling multiple observations at short intervals from the LLNL site.

The experimental configuration and sequence of events was as close as possible to what would be expected on orbit. The observations were scheduled using the NORAD catalog, and were uploaded into the payload with the correct pointing and timing information. The payload was then under normal on-orbit operation, using the on-board GPS for location and time synchronization. The spacecraft attitude control system was emulated by using a Celestron mount fitted with an Orion Finder scope as star tracker. The first four observations captured in the course of just over 24 hours were processed through step 4 and 5 of our concept of operation described previously, and the refined orbits were propagated to the epochs of the 5th and 6th observation, as shown in Figure 6. Observations 5 and 6 were used as ground truth to assess the accuracy of the prediction over various extrapolation times in the future (12.8 hours for the 5th observation and 35.5 hours for the 6th observation).

The optics and sensor performance as built was within specifications as described in the previous section. In particular, the size of the resulting point spread function was comparable to what would be expected on orbit with the final pathfinder optical design and nominal attitude control performances. The aperture is 85 mm and the read noise is measured at 13e- (rms). The system equivalent point spread function was measured to be 2.4 pixels FWHM.

The results from this ground campaign achieved a level of orbital refinement accuracy well below the 100 m required (see Table 8). While this object is quite large, using a Lambertian scattering model and scaling the range from the actual ~1500 km value to the expected values in the constellation of a few hundred km, one can estimate the equivalent smallest detectable size of an object at closer range. For this particular sensor and optics combination, we expect a detection threshold of a 20 cm × 20 cm object at 100 km range with a transverse velocity of 1 km/s.

CONCLUSION

A capability gap has been identified regarding the ability to meaningfully provide potential collision warnings that can be actionable by space operators. The STARE mission developed at LLNL can close this gap using a non-traditional approach based on a constellation of low cost nano-satellites. This approach reduces the overall cost and provides operational redundancy due to the multiplicity of space assets. Furthermore, nano-satellites have a limited lifetime estimated to about 2 years and require periodic replenishment, which allows for rapid adaptability and virtually no significant aging of the capability as a whole.

The requirement flow down presented here, as well as the ground performance validation, demonstrates the effectiveness of this mission and sets the technical framework towards an operational system. The upcoming pathfinders are expected to raise the technology readiness level (TRL) to 7 by exercising refinement in an in-orbit operational environment. LLNL is offering a technology and business opportunity under FBO245 to lead the path towards transitioning this technology into operation.

DISCLAIMER

ACKNOWLEDGMENT

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